Engineering Notes

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Optimum Flap Schedules and Minimum Drag Envelopes for Combat Aircraft

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Nomenclature

A	= aspect ratio
b	= wing span
$c(\eta)$	= local chord
C_D	= total drag coefficient
C_{DL}	= lift-dependent drag coefficient
C_{DLm}	= minimum drag envelope
C_{DPL}	= lift-dependent profile drag coefficient
C_{DV}	= vortex drag coefficient
C_L	= lift coefficient
$C_{L_\alpha}, C_{L_\beta} C_{L_\gamma}$	= wing lift curve slope with respect to angle of attack, leading-edge flap deflection angle, and trailing-edge flap deflection angle, respectively
C_d	= sectional drag coefficient
$C_{d_{\min}}$	= minimum profile drag
C_1	= section lift coefficient
C_{1_i}	= lift coefficient at minimum drag—also ideal lift coefficient
F	= quantity proportional to C_{DPL}
K_P	= lift-dependent profile drag factor
K_T	= lift-dependent drag factor of minimum drag envelope
k	= lift-dependent drag factor for a section
L/D	= lift-to-drag ratio
S	= wing area
y	= spanwise station
α	= angle of attack (with respect to wing chordal plane)
$\alpha_{i0}(\eta)$	= distribution of total induced angle of incidence
β	= leading-edge flap deflection angle
γ	= trailing-edge flap deflection angle
$\Gamma(\eta)$	= spanwise loading
η	= $y/(b/2)$-nondimensional spanwise station
ΔC_P	= chordwise loading
β_{opt}	= optimum leading-edge flap deflection angle
γ_{opt}	= optimum trailing-edge flap deflection angle

Introduction

WING leading- and trailing-edge flaps are usually deployed to improve the lifting ability of wings, especially during takeoff and landing. In recent times, however, these flaps have been used also during maneuver conditions to improve the aerodynamic efficiency (L/D). Some examples of aircraft using such devices are F-4E, F-5E, F-16, F-18, etc. During a maneuver, the flaps automatically follow a predetermined deflection schedule which is a function of Mach number and angle of attack. The flap deflection schedule is mainly determined through extensive wind-tunnel tests.

In this paper, a simple analytical method based on linear theory is developed to determine the optimum flap schedule for both leading- and trailing-edge flaps.

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Problem Formulation and Method of Solution

If the drag polars are plotted for various flap deflections β and γ, then the envelope of these polars defines the minimum drag envelope. The corresponding deflections β_{opt} and γ_{opt}, which minimize the lift-dependent drag C_{DL}, define the optimum flap schedule.

Lift-Dependent Profile Drag

For a cambered airfoil, the drag polar can be fairly well represented by the relation

$$C_d = C_{d_{\min}} + k(C_1 - C_{1_i})^2 \tag{1}$$

To a first approximation, C_{1_i} and C_d can be taken to be functions of camber alone. Extending these arguments to each spanwise section of a three-dimensional wing (i.e., assuming that the wing is composed of a series of two-dimensional airfoils of varying camber and thickness), the lift-dependent profile drag C_{DPL} can be determined by integrating Eq. (1) across the span and is written as

$$C_{DPL} = \frac{1}{S}\int_{-b/2}^{b/2} K_p (C_1 - C_{1_i})^2 c \, dy = K_p F \tag{2}$$

where K_P is a constant (being independent of camber), and

$$F = \frac{1}{S}\int_{-b/2}^{b/2} (C_1 - C_{1_i})^2 c \, dy \tag{3}$$

For a wing at an incidence α, $C_1(\eta)$ and C_{1_i} can be expressed in accordance with linear theory as

$$C_1(\eta) = a_1\alpha + a_2\beta + a_3\gamma$$

$$C_{1_i} = a_4\beta + a_5\gamma \tag{4}$$

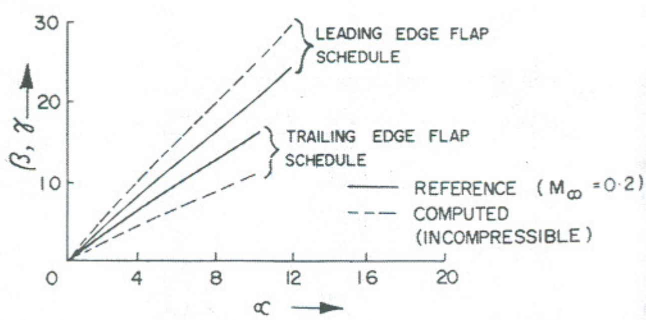

Fig. 1 Flap schedule of F-18 aircraft.

where $a_1, \ldots, a_5$ are constants. Substituting these in Eq. (3) and carrying out the integration, F can be expressed as a quadratic in C_L, β, and γ:

$$F = A_1 C_L^2 + A_2\beta^2 + A_3\gamma^2 + A_4\beta C_L + A_5\beta\gamma + A_6\gamma C_L \quad (5)$$

Here, $C_L = C_{L_\alpha}\alpha + C_{L_\beta}\beta + C_{L_\gamma}\gamma$ for small α, β, and γ.

The lift-dependent profile drag factor K_P is determined by the use of data correlation curves given in Refs. 1 and 2. The ideal lift coefficient C_{l_i} and zero lift incidence on stations of wing with deflected flaps are calculated using the local loading ΔC_P and $C_l(\eta)$ formulae given in Ref. 3 modified to include a leading-edge flap. The details of these calculations are given in Ref. 4.

Vortex Drag

McKie's method[3] for calculation of spanwise load distribution on wings with spanwise discontinuities in angle of incidence and/or wing chord has been adopted here for wings with plain leading- and trailing-edge flaps. Once the load distribution $\Gamma(\eta)$ is known, the spanwise distribution of local lift $C_l(\eta)$ is related to $\Gamma(\eta)$ by

$$C_l(\eta) = (2b/c)\Gamma(\eta) \quad (6)$$

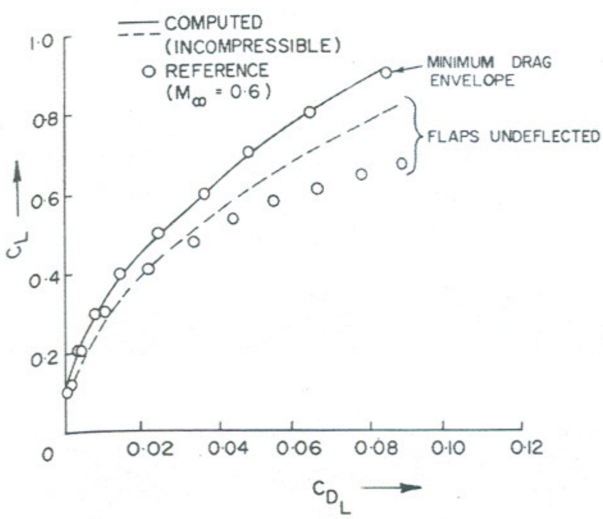

Fig. 2 F-18 minimum drag envelope.

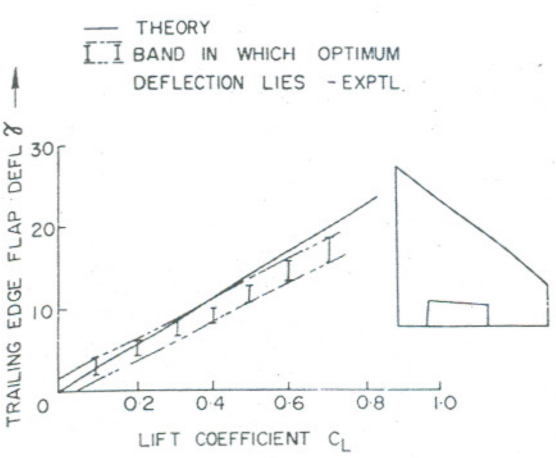

Fig. 3 Trailing-edge flap schedule.

The total lift and vortex drag coefficients are

$$C_L = A\int_{-1}^{+1} \Gamma(\eta)\, d\eta \quad (7)$$

$$C_{DV} = A\int_{-1}^{+1} \Gamma(\eta)\alpha_{i0}(\eta)\, d\eta \quad (8)$$

Within the limits of linear theory, C_{DV} can be expressed as a quadratic

$$C_{DV} = B_1 C_L^2 + B_2\beta^2 + B_3\gamma^2 + B_4\beta C_L + B_5\beta\gamma + B_6\gamma C_L \quad (9)$$

where $B_1, B_2, \ldots, B_6$ are constants.

Total Lift-Dependent Drag

Since both C_{DV} and F are quadratic in C_L, β, and γ, the total lift-dependent drag is also a quadratic and can be expressed as

$$C_{DL} = C_{DV} + K_P F = C_1 C_L^2 + C_2\beta^2 + C_3\gamma^2 + C_4\beta C_L + C_5\beta\gamma + C_6\gamma C_L \quad (10)$$

where $C_1, C_2, \ldots, C_6$ are constants.

Flap Schedule and Minimum Drag Envelope

To get the flap schedule, C_{D_L}, Eq. (10) is minimized with respect to β and γ for a given C_L. The first derivatives of C_{D_L} with respect to β and γ are equated to zero. The resulting values of β_{opt} and γ_{opt} are substituted in Eq. (10), and the minimum drag envelope is given by

$$C_{D_{Lm}} = K_T C_L^2 \quad (11)$$

where K_T is a constant and the constants $C_1, C_2, \ldots, C_6$ are determined by knowing the total lift-dependent drag coefficient for various values of β and γ.

Results

Figure 1 gives a comparison of leading- and trailing-edge flap schedules and Fig. 2 the resulting minimum drag envelope for F-18 aircraft.[5] The comparison of flap schedules between theory and experiment for the F-18 aircraft (Fig. 1) does not seem to be very good. A possible reason for this could be the relative insensitivity of the drag coefficient to flap deflection angle, at least around the flap angles for minimum drag and at the lift coefficients under consideration.

Figure 2 shows that for the undeflected flap case, the estimated drag departs from the experimental one for $C_L > 0.4$, indicating the limits of the linear theory. However, with the flaps deflected (both leading and trailing edge), the agreement between experiment and estimation is remarkably good even for C_L of about 0.9. This can possibly be attributed to the ability of the leading-edge flaps in maintaining attached flow at these high C_L values.

A comparison of the drag envelope for the F-16 aircraft with and without programmable leading-edge flaps was made. The decrease in C_{D_L} when flaps are employed is quoted as 18% in Ref. 6, which compares well with about 15% obtained from the present method. Figure 3 displays another comparison between theory and tests conducted at the National Aeronautical Laboratory on an aircraft model (aspect ratio $A = 3.2$) at a Mach number of 0.5. These tests were done with and without trailing-edge flaps deflected. Figure 3 shows that the trailing-edge flap deflection schedule is predicted reasonably well by the theory.

Conclusions

A simple method based on linear theory has been developed for the determination of trailing- and leading-edge flap deflection schedules to obtain minimum lift-dependent drag (or equivalently maximum lift-to-drag ratio). The resultant lift-dependent drag polar can also be determined. Extensive comparisons with available experimental results have proved the general validity of the method. It is expected that this method would be useful in the preliminary design phase of an aircraft and also in reducing later on the quantum of wind-tunnel testing needed to determine flap schedules.

Acknowledgments

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